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Single photoionization of aluminum-like P^{2+} and magnesium-like P^{3+}

L. Hernández [a], A.M. Covington [b], E.M. Hernández [a,d], A. Antillón [a], A. Morales-Mori [a], Kiattichart Chartkunchand [b], A. Aguilar [c], G. Hinojosa [a,*]

[a] Universidad Nacional Autónoma de México, Instituto de Ciencias Físicas Apartado Postal 48-3, Cuernavaca 62251, México.
[b] Department of Physics, University of Nevada, Reno, NV 89557-0220, USA.
[c] The Advanced Light Source, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[d] Facultad de Ciencias, Universidad Autónoma del Estado de Morelos, Avenida Universidad 1001, Cuernavaca 62209, México.

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ABSTRACT

Absolute single-photoionization cross sections for aluminum-like P^{2+} have been measured from 26.5 to 66.5 eV using photoion yield spectroscopy. In addition, absolute cross section measurements for the single-photoionization of magnesium-like P^{3+} have been measured from 43 to 60 eV. For both ions, the measured spectra are dominated by Rydberg series resonances superimposed on a non-resonant direct photoionization cross section. Analyses of these data have helped identify the initial and final states of the Rydberg series observed in each photoion. In addition, quantum defects are derived for each series.

1. Introduction

Phosphorus is among the 20 most abundant elements in the Universe and together with hydrogen, carbon, nitrogen, oxygen and sulfur, it is a necessary element for life. The determination of accurate cosmic abundances from astrophysical observations is limited by the lack of laboratory-measured photoionization data available in the literature. These data are necessary to help determine ion number densities as light propagates from an object to the observer through an absorbing medium. Until recently, phosphorus photoionization data was limited to discharge lamps [1] and theoretical models of the isoelectronic systems [2]. The photoionization data presented are intended to help benchmark these types of efforts.

Understanding the observed abundances of phosphorus is still an important question; Caffau and collaborators [3] proposed the possibility that phosphorus could be formed in late stages of stars. Later, Bon-chul et al. [4] found evidence of phosphorus in supernovae by measuring the infrared spectra in the remnants of Cassiopea A. In addition, extragalactic phosphorus has been observed in the solar photosphere by Caffau et al. [5], in solar twins by Meléndez et al. [6], in the infrared spectrum of Messier 77 galaxy (NGC 1068) by Oliva et al. [7] and in globular clusters by Hubrig et al. [8].

From a fundamental atomic physics point of view, isoelectronic quantum mechanical systems provide useful information because of the similarities in the atomic eigenfunction expansions [2]. For instance, Mg has two valence electrons and during its photoionization, the double electron excitation is an important process. P^{3+} is isoelectronic with atomic Mg and presents an opportunity to study a more complex two-electron system. To our knowledge, measurements for both P^{2+} and P^{3+} photoionization cross sections are very rare. For the case of P^{2+}, we are aware of the work of Magnusson and Zetterberg [1], who performed emission spectroscopy in a discharge gas in the range of 1.27–62.00 eV. They achieved

* Corresponding author.
E-mail address: hinojosa@fis.unam.mx (G. Hinojosa).

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the classification of several spectroscopic terms, ionization limits and spectroscopic lines.

In addition to its fundamental interest, the photoionization of P^{2+} has relevance in applied plasma equilibrium, for instance, Jupén and Curtis [9] measured spectra from a JET emitted plasma from a Tokamak; they observed transitions from Mo^{29+} and Kr^{23+} and identified a $3s^2$ 3p to $3s3p^2$ aluminum-like transition. Raineri et al. [10] studied aluminum-like Ar^{5+} and accomplished the classification of several new lines from plasma-discharge spectra.

In the case of atomic Mg, Preses and collaborators [11] studied the photoionization of Mg near threshold by detecting Mg^+ ion yield generated with monochromatized synchrotron radiation. They identified two-electron excitation followed by autoionization. Butler et al. [12] used the close-coupling approximation to study the Mg isoelectronic sequence in the collisional formalism. Chi and Huang [13], used a multi-configuration approximation theory and found three Rydberg series of the fine structure splitting in the initial states of Mg. Dae-Soung and Tayal [14] and Dae-Soung [15], performed variational R-matrix calculations to derive position resonance energies, quantum defects and widths for several doubly excited states of Mg. Hsiao and Huang [16] used multi-configuration relativistic random-phase approximation to study atoms with two valence electrons outside a closed shell.

Ionization limits and spectroscopic lines for all charge states of phosphorus have been systematically classified and calculated by Biémont et al. [17] by Martin et al. [18] and by NIST [19].

In this work, we present spectroscopic and absolute cross section measurements for the single photoionization of P^{2+} leading to P^{3+} and for P^{3+} leading to P^{4+} with a photon energy resolution of 35 meV. These results will likely assist abundance determinations and line identifications from spectroscopic observations.

2. Experiment

The phosphorus ion targets consisted of mass-to-charge analyzed ion beams that interacted with a monochromatic photon beam from beamline 10.0.1.2 in the Advanced Light Source synchrotron at the Lawrence Berkeley National Laboratory. This was achieved by using the merged-beams technique [20,21] that consists in overlapping two beams over a common collinear path. In this case, a photon beam was merged with an ion beam of either P^{2+} or P^{3+} (which will be called *parent ion beams* from here on). As a result of the interaction of both beams, the parent ion beam may ionize again, forming ions (*photoions*) with a higher charge. These photoions and the remaining parent ion beam were mass-separated and counted. In this technique, significant parameters of both beams and their overlap are measured. The method has been described in detail in previous measurements of photoionization cross section for Ne^+ [22]. A general description of the experiment with some details relevant to the present work will be given here.

The ultraviolet light required to photoionize P^{2+} or P^{3+} parent ions was generated with a 10-cm-period undulator positioned in the synchrotron storage ring that operated with a constant electron current of 0.5 A at 1.9 GeV. This yielded a collimated photon beam of maximum width of 1.5 mm and with a divergence less than 0.06°. The photon beam was then directed to a spherical-grating (in grazing incidence mode) set in a configuration that allowed changes to the photon beam energy by rotating the grating and translating the exit slit of the monochromator while simultaneously adjusting the undulator gap to maximize the photon-beam intensity.

The photon flux was measured with an absolute-calibrated silicon photodiode with an accuracy of 5%. The signal from the silicon diode was monitored by a precision current-meter analog output of which was fed to a voltage-to-frequency converter to provide a normalization photon flux signal to the beamline computer interface. The photon beam was pulsed by using a chopper wheel that separated the resulting photoions from ions of the same charge produced by collisions with the residual gas in the vacuum chamber.

To calibrate the photon energy, we used photon ionization energies of He [23] and Kr [24] in the energy range from 21.218 eV to 63.355 eV. This procedure was performed in a side branch gas-cell and yielded a photon energy uncertainty of $\pm$ 10 meV.

The P^{2+} and P^{3+} ion beams were generated by mixing Ar and PF_3 gasses in a permanent-magnet ECR ion source. Ions were accelerated from the source to a kinetic energy of 12 keV for P^{2+} and 18 keV for P^{3+} respectively. A 60° sector analyzing magnet was used to accurately mass-to-charge select the P^{2+} or P^{3+} cations. A cylindrical Einzel lens, located before the analyzing magnet, was used to focus the ion beam.

Ion beams were merged onto the axis of the counter propagating photons with a set of electrostatic 90° spherical sector bending plates. The ions then entered a biased cylindrical interaction region (IR), which energy labeled the P^{3+} or P^{4+} daughter photoions that were subsequently separated from the primary P^{2+} or P^{3+} ion beams, respectively, with a 45° dipole analyzing magnet.

The overlap between the ion and photon beams was derived from mechanically controlled, two-dimensional, beam profilers located at the entrance, center and exit of the IR. The measured beam profiles were used to calculate the interaction volume between the ion and photon beams, therefore allowing us to derive absolute cross sections.

The parent ion beams were collected in an extended Faraday cup. The magnetic field was set such that the product photoions generated in the interaction region passed through an aperture located in the back of the Faraday cup. An additional spherical electric field deflected the photoions to a biased stainless steel plate from which secondary electrons were accelerated and detected by a channel electron multiplier.

The spectra shown in Figs. 1 and 3 were measured in 1 eV wide photon energy intervals overlapped by 0.5 eV. All the individual 1 eV wide spectra were later combined by joining adjacent regions to produce the entire measured spectrum. This method was used to try to reduce effects of a slight mechanical backlash from the monochromators and to improve the automatic photon flux optimization adjustments in the photon beamline. We estimate that the overall photon energy error caused by this effect and the gluing procedure was not greater than $\pm$ 8 meV. The overall energy uncertainty propagated by both the gas-cell energy calibration and the data reduction procedure was $\pm$ 13 meV.